Extending of "Quasar" VLBI-Network: VGOS-compatible Radio Telescope in Svetloe

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Abstract IAA RAS has finished the construction of a new radio telescope in Svetloe, and the first fringes will be received in September of 2018. The new 13.2-m antenna will extend the facilities of the "Quasar" VLBI-network to six radio telescopes, and it will be the first one fully compatible with other VGOS stations worldwide. This paper is focused on equipment that makes it possible. The equipment of the Badary and Zelenchukskaya stations will also be upgraded soon to allow all three observatories of "Quasar" to join the international VGOS network.

1 Introduction

The Russian VLBI-network "Quasar" currently consists of three observatories: Zelenchukskaya, Badary, and Svetloe [1]. The 32-meter radio telescopes (RT-32) located at each of the observatories are part of international VLBI-networks (IVS and EVN), and they participate in many international and domestic observations. Since 2015 in Zelenchukskaya and Badary, there have been fast 13-meter radio telescopes (RT-13) operating in S/X/Ka wideband mode, mostly for domestic programs [2]. The antennas of RT-13 are VGOS-compatible, but they are equipped with Tri-band receivers and the Broadband Acquisition System that do

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not fully correspond to VGOS requirements. In 2018, the Svetloe observatory also got a new RT-13 radio telescope. The equipment of the new antenna is mostly ready, and the first fringes are going to be received in September 2018. The important point is that the new antenna is equipped with two types of receivers: both Tri-band and Ultra-wideband (UWB). The last one is VGOS-compatible and in conjunction with the new Multifunctional Digital BackEnd (MDBE), making it possible for the new radio telescope to join the international VGOS network. This paper is focused on the equipment of the new antenna that allows this.

2 Receiving System

The new antenna at Svetloe can be equipped with either a Tri-band (Figure 1) or a UWB (Figure 2) receiver. All parts are designed to allow easy and fast interchange of the receivers that takes just around six hours. It makes switching between the existing networks observing in S/X/Ka bands and the VGOS network possible.

The Tri-band receiver is similar to the ones used on RT-13 in Badary and Zelenchukskaya [3]. It simultaneously receives signals in S, X, and Ka bands in both circular polarizations. Both feed and low noise amplifiers (LNAs) are cryogenically cooled to keep the noise temperature low. Noise and phase calibration signals are injected into the signal chain before the LNAs.

Up-down converters (UDC) move the signals' required radio frequency range to intermediate frequencies (IF) used by the digital backend (from 1 to 2 GHz). In each polarization there are three UDCs for X-band, one UDC for S-band, and three UDCs for Ka-band. In total this gives 14 IF signals. By using a commutator,
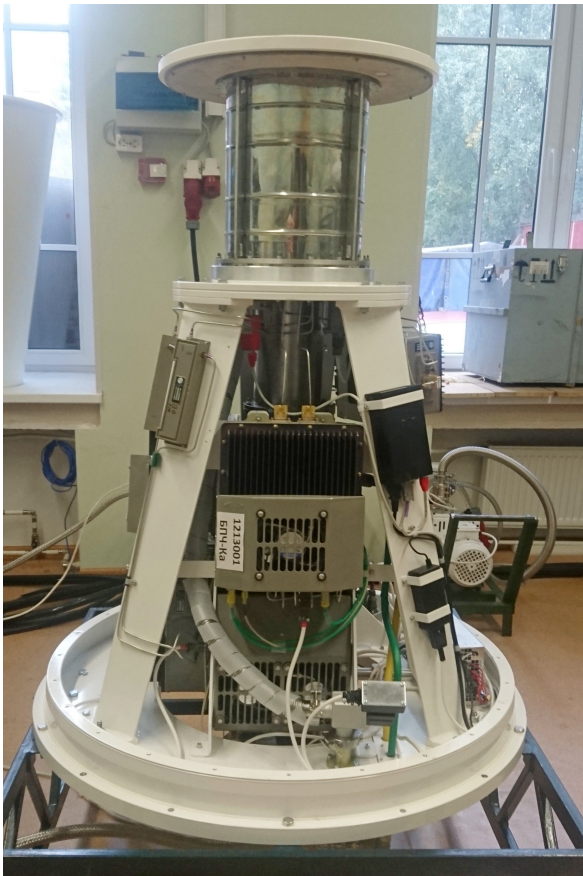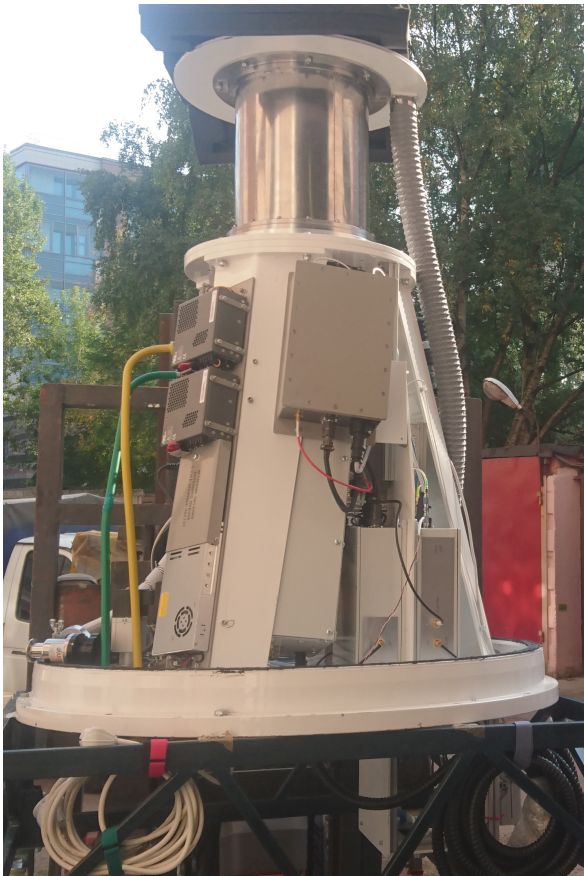
Fig. 1 The Tri-band receiving system.

Fig. 2 The ultra-wideband receiving system.

eight of them are available outside of the receiver and transmitted to the digital backend.

Unlike the Tri-band receiver, the UWB receiver has a continuous frequency range from 3 to 16 GHz [4]. It uses a cryogenically cooled feed of QRFH type. Noise and phase calibration signals also can be used and injected into the signal chain before the LNAs. There are four UDCs in the receiver for each of the linear polarizations. The output signals of the UDCs lie in the frequency range of 1 to 2 GHz and are directly connected with the digital backend. Key parameters of the Tri-band and UWB receivers are summarized in Table 1.

Table 1 Key parameters of the Tri-band and UWB receiving systems.

Parameter	Tri-band	UWB
Input frequency range	2.2-2.6 GHz (S-band)	3-16 GHz
	7.0-9.5 GHz (X-band)	
	28-34 GHz (Ka-band)	
Polarizations	Dual circular	Dual linear
Noise temperature	< 35 K (S-band)	<50 K
	< 33 K (X-band)	
	< 80 K (Ka-band)	
Step of local oscillators	0.1 MHz in S-band	0.4 MHz
	0.4 MHz in X/Ka-bands	
Output IF range	1-2 GHz	1-2 GHz
Output channels	(1 S + 3 X) x 2 pol. (8 total)	4 x 2 pol.
	(1 X + 3 Ka) x 2 pol. (8 total)	
	(1 S + 2 X + 1 Ka) x 2 pol. (8 total)	

3 Digital Backend

Currently, the RT-13 at Svetloe is equipped with the Broadband Acquisition System (BRAS) that is the

same as at the Zelenchukskaya and Badary observatories [5]. This system digitizes up to eight input signals in the frequency range between 1 and 1.5 GHz. Each signal is quantized to 2-bit samples with the root mean square value as a threshold. The data is then packed into VDIF frames without any sub-channelization and comes to the recording system over fiber link through a 10 G Ethernet interface. BRAS is a simple and low cost system, but it supports only 512 MHz bandwidth per channel and the only mode of operation. Because of these limitations it does not completely meet VGOS requirements, although it has been successfully used since 2015 for domestic observation programs.

In 2019, BRAS will be replaced with the new Multifunctional Digital BackEnd (MDBE) that is free of the listed limitations. The MDBE contains up to 12 DSP units (Figure 3 and Figure 4) that can digitize either one signal of 2 GHz bandwidth or two signals of 1 GHz bandwidth. Each DSP unit is based on a powerful FPGA that can perform quite advanced signal processing compared with the DSP units of BRAS. In conjunction with the remote firmware reconfiguration, it allows implementation of any required operational mode, including digital downconverter mode, to maintain compatibility with other astronomical backends. It also supports single dish modes for radiometric and spectrometric observations.

Besides its main purpose, the MDBE performs some signal analysis features like full input power measurement and PCAL extracting. Monitoring PCAL tones in time gives useful information about equipment stability and overall signal chain health. These features are very convenient for the equipment debugging and early detection of faults and performance degradation. To help hardware debugging, the MDBE can also perform FFT of input signals and can capture raw data from ADCs.

As timing issues are very important for VLBI applications, the MDBE has a number of tools to control it. The system clock is synchronized with the clock of the radio telescope by using a 1 PPS signal. The MDBE constantly monitors the delay between internal and external clocks to detect any jumps. It also can monitor the difference with the GNSS receiver clock. To take into account the fine effects of instrumental delay variations, the MDBE provides calibration loops to measure variations in the sampling clock synthesizer and clock distribution network. The key parameters of the MDBE are summarized in Table 2. In gen-

eral, the MDBE will expand functionality of the radio telescopes and will unify backend equipment over the "Quasar" VLBI-network. It also will help to achieve compatibility with other VLBI radio telescopes worldwide.

Table 2 Key parameters of the MDBE.

Input bandwidth of DSP unit	Up to 2 GHz
Number of DSP units	Up to 12
Data rate	Up to 96 Gbps (2-bit quantization)
Data outputs	VDIF, 10GbE/40GbE, Fiber link
Remote reconfiguration	yes
Operational modes	VLBI: wideband channels, DDCs, PFB
	Single-dish: spectrometer, radiometer
Auxiliary features	PCAL extraction and analysis
	Internal delay instability measurement
	Embedded CDMS
	Signal capturing and FFT

4 Recording System

The data recording system for the new antenna is similar to that used for the other RT-13s [6], [7]. It is based on commercial, off-the-shelf hardware and provides recording of eight channels from the MDBE or BRAS with a total data rate up to 32 Gbps. The recording system supports transferring data to the Correlation Center of IAA RAS simultaneously with data recording. It helps to achieve low latency of VLBI results. The capacity of the storage is up to 200 TB, allowing data to record for a full day of observation programs.

5 Time and Frequency Transfer System

The time and frequency transfer system (TFTS) transmits required clock signals from the H-maser to equipment inside the focal cabin of the antenna. The MDBE, local oscillators of the receiving system, and PCAL generator use a 100 MHz signal as a reference clock. It comes to the focal cabin through the fiber line and is distributed to consumers through short and phase stable coaxial cables.

The TFTS includes a loopback to implement a cable delay measurement system (CDMS). It uses the same fiber to send back a received clock signal on
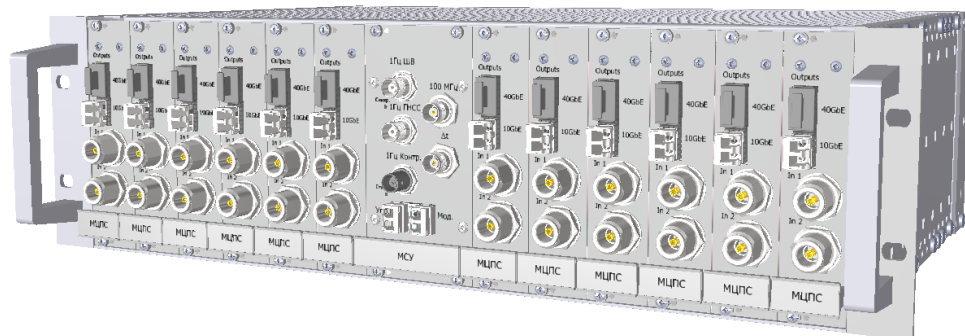
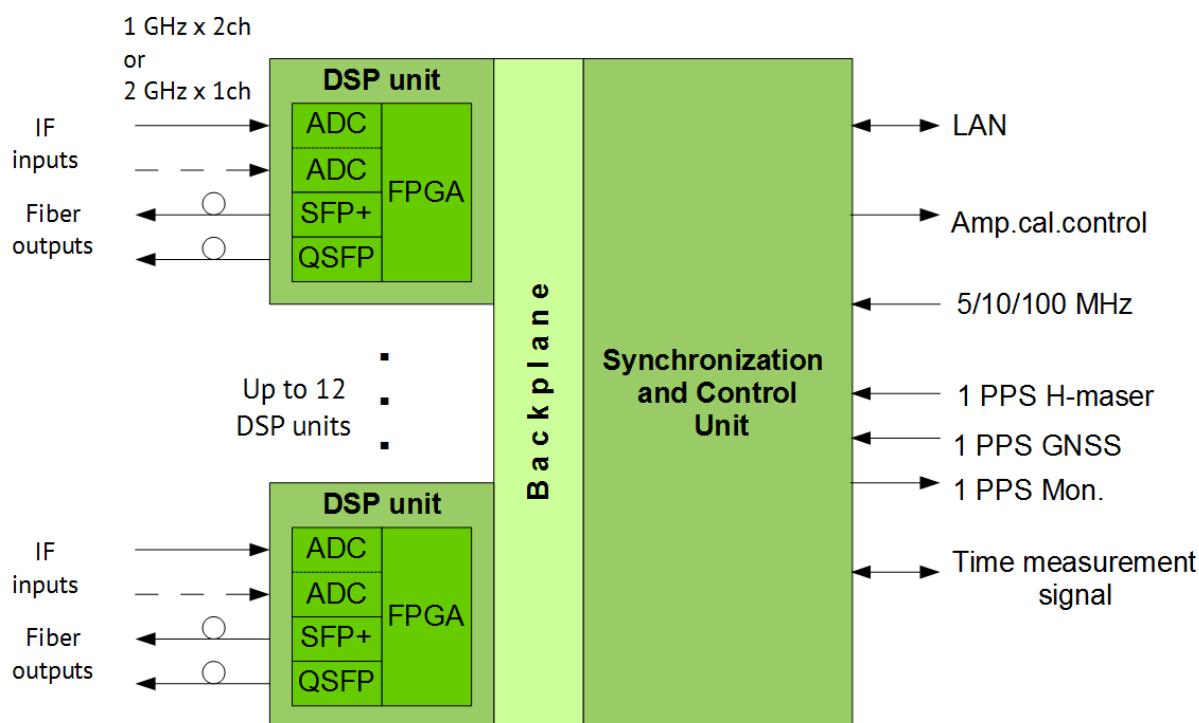**Fig. 3** A 3D model of the MDBE.

Fig. 4 An MDBE structure.

another optical wavelength. The CDMS allows measurement of cable delay variations at the 1 ps level. 1 PPS signals are also transferred to the focal cabin over fibers.

6 Conclusions

The construction of the new radio telescope RT-13 in Svetloe is finished. The first fringes are expected in September 2018. The newly created RT-13 is equipped with a Tri-band receiving system to provide regular observations with the other RT-13 antennas of

the "Quasar" VLBI-network. A new ultra-wideband receiving system is also ready for testing to allow joint observations with VGOS stations. The new Multifunctional Digital BackEnd will help to achieve full compatibility with other known backends used for VLBI.

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